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Double Boson Production at CDF

Dirk Neuberger
For the CDF Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

University of California
Los Angeles, California 90095

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DOUBLE BOSON PRODUCTION AT CDF

DIRK NEUBERGER [a]
University of California, Los Angeles,
CA 90095, USA

For the CDF Collaboration

New measurements of boson pair production in $p\bar{p}$ collisions have been performed by the CDF collaboration using a data sample of approximately 110 pb^{-1}. The cross sections for WW and WZ production are measured in the pure leptonic decay channel to $\sigma(p\bar{p} \to WZ) = 3.2^{+5.0}_{-3.2}$ pb and $\sigma(p\bar{p} \to W^+W^-) = 10.2^{+6.5}_{-5.3}$ pb, respectively. Limits on anomalous coupling parameters are set in the searches for WW and WZ production. Assuming an energy scale of $\Lambda_{FF} = 2$ TeV, we find for the WWZ and $WW\gamma$ couplings at 95% CL: $-0.4 < \lambda < 0.3$ ($\Delta\kappa = 0$) and $-0.5 < \Delta\kappa < 0.5$ ($\lambda = 0$).

1 Introduction

With the end of the Tevatron Run I, CDF has collected approximately 110 pb^{-1} of data in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV

In this paper, we present new CDF measurements of the production cross section of WW and WZ pairs and briefly summarize all diboson production cross sections measured by CDF to date. We further report on improved limits on WWγ and WWZ couplings and mention noteworthy multi-boson candidates.

Diboson production is fully described by the Standard Model. This model predicts the presence of three-boson couplings such as WWW, WWZ or WWγ, and the absence of ZZZ, ZZγ or Z$\gamma\gamma$ couplings. Three-boson vertices are characterized by coupling parameters which vanish individually at the tree level Standard Model (SM). If non-SM, i.e. anomalous three-boson couplings existed in nature, an increase in the diboson production rate could be observed in the experiment. In order to avoid unitarity violation of the theory, the coupling parameters have to be modified by form factors

$$\xi(\hat{s}) = \frac{\xi_0}{(1 + \hat{s}/\Lambda_{FF}^2)^n},$$

with a theory-dependent exponent n and a form factor scale Λ_{FF}. For energies beyond Λ_{FF}, new physics is presumed [1].

[a] Present address: Universität Karlsruhe, Postfach 6980, 76128 Karlsruhe, Germany

Table 1: Comparison of the number of measured WZ events to the total background.

Channel	Background	Events
(W $\rightarrow e\nu$) + Z	0.24 ± 0.2	1
(W $\rightarrow \mu\nu$) + Z	$0.06^{+0.8}_{-0.0}$	0
(W $\rightarrow \ell\nu$) + Z	$0.30^{+0.8}_{-0.3}$	1

2 Weak Boson Identification

The selection of leptonically decaying weak bosons is similar in all following analyses: An isolated *electron* or *muon* with a transverse energy above $E_T = 20$ GeV is searched for in a fiducial region of the CDF detector. The rapidity of the lepton is constrained to the central region ($|\eta| < 1.1$), with the exception of the $WW \rightarrow \ell\ell + X$ analysis where additionally leptons with $E_T > 10$ GeV in the rapidity range $1.1 < |\eta| < 2.4$ are included.

A W boson is defined by requiring a missing transverse energy of $\not{E}_T > 20$ GeV. A Z boson is defined by an electron or muon pair with a mass close to the Z mass. The second Z decay lepton with $E_T > 10$ GeV may be found up to rapidities of $|\eta| < 2.4$.

3 Production of WZ, $ZZ \rightarrow$ *leptons*

In order to extract WZ and ZZ events, a total of 11161 leptonically decaying Z candidates are searched for a third and fourth lepton in the event. If—in a three-lepton event—there is more than one dilepton pair that forms a Z mass, the event is rejected. After applying all lepton selection criteria, only one three-lepton event with large missing E_T, interpreted as a WZ candidate, and no four-lepton event, i.e. no ZZ candidate remain.

There are three likely background sources in the WZ analysis: these are pairs of 1.) Z plus fake W, 2.) W plus fake Z and 3.) Z plus fake Z bosons. Since the Z signal is clean, the predominant background is due to fake W bosons in Z + jet events where the jet is misidentified as a lepton: By studying independent data sets of Z + jet and Z + isolated track events, we determine the Z + fake W production rate in the electron and muon decay channel, respectively. Applying these results to the number of WZ candidates found, we obtain $N_e(W_{fake}Z) = 0.2 \pm 0.2$ and $N_\mu(W_{fake}Z) = 0.0^{+0.8}_{-0.0}$.

From an analysis of the sidebands of the Z mass distribution, contributions of W/Z + fake Z events are found to be negligible. Using Pythia [2], we estimate the number of ZZ events where one of the Z decay leptons is not detected to 0.028 and 0.055 in our electron and muon WZ data sets, respectively. Tab. 1

Table 2: $W^+W^- \to \ell^+\ell^- + X$ search: a.) Number of background events before and after applying a jet veto; b.) Overall efficiencies $\times$ acceptance, ϵ_{tot}, and number of observed W^+W^- events, N_{obs}, in each dilepton channel.

a.) Background		
Process	no 0-jet cut	all cuts
Drell Yang	1.90	0.43 ± 0.21
W+jet	1.80	0.40 ± 0.20
WZ	0.17	0.12 ± 0.05
$Z \to \tau\tau$	0.59	0.22 ± 0.06
$t\bar{t}$	5.00	0.04 ± 0.01
$b\bar{b}$	< 0.1	< 0.1
Total Bkgr.	9.58	1.21 ± 0.30

b.) Event Selection		
Dilepton Channel	ϵ_{tot}	N_{obs}
e^+e^-	4.88 ± 0.59	2
$\mu^+\mu^-$	5.40 ± 0.65	0
$e^\pm\mu^\mp$	8.86 ± 1.06	3

summarizes the total backgrounds and compares them to the number of events found in each decay channel.

In studies of Monte Carlo and data set, the total efficiency $\times$ acceptance was calculated to be $\epsilon = 0.191 \pm 0.025\%$. Hence, with an integrated luminosity of 113 pb^{-1}, we measure after background subtraction a WZ production cross section of

$$\sigma(p\bar{p} \to WZ + X) = 3.2^{+5.0}_{-3.2}\ \text{pb},$$

in good comparison with the SM prediction (Fig. 4).

4 Production of $W^+W^- \to \ell^+\ell^- + X$

In the dilepton channel, the kinematics of W bosons in W pair production resembles the one of W bosons in $t\bar{t}$ decays. As a consequence, the selection criteria are similar in both analyses, and $t\bar{t}$ decays represent a major background source in the $W^+W^- \to \ell^+\ell^- + X$ search.

To discriminate against $t\bar{t} \to W^+W^-b\bar{b}$ production, WW events are rejected if they contain any jet with an uncorrected $E_T > 10$ GeV in a cone of radius $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$. This jet veto also reduces other background contributions from WZ, W+jet, $Z \to \tau\tau$ and Drell Yang processes. The latter two are already suppressed by excluding events in the dilepton mass window $75 < M_{\ell^+\ell^-} < 105\ \text{GeV/c}^2$, and by removing events where the azimuthal separation between the direction of the $\not\!\!E_T$ vector and the nearest lepton is smaller than $20°$.

Applying all selection criteria to the data set of 108 pb^{-1}, five WW candidates are found. Using the calculated SM W^+W^- cross section [4] of 9.5 pb, we expect 3.5 ± 1.2 events. The total background estimate amounts to 1.2 events.

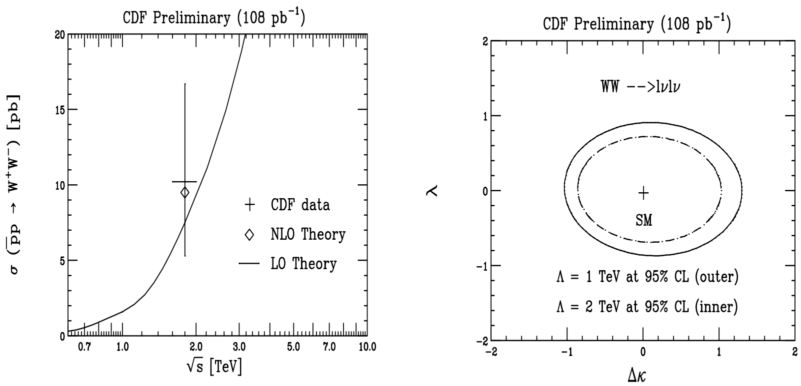


Figure 1: a.) Measured and calculated W pair production cross sections. b.) Limit contours on the anomalous WWZ and WWγ couplings from the analysis of leptonic WW decays, assuming $\lambda_Z = \lambda_\gamma$ and $\kappa_Z = \kappa_\gamma$.

Tab. 2 summarizes the results. The backgrounds and the overall selection efficiencies are obtained using Monte Carlo and data samples. Hence, we measure the W^+W^- production cross section in $p\bar{p}$ collisions to

$$\sigma(p\bar{p} \to W^+W^-) = 10.2^{+6.5}_{-5.3} \text{ pb},$$

in good agreement with QCD leading order [3] and next-to-leading order [4] SM calculations (Fig. 1 a.). We expect from the small difference between the LO and NLO calculation, that the jet-veto has a negligible effect on our result.

By comparison of the observed number of events to the expected number of events in the presence of anomalous WWV (V=Z,γ) couplings λ and $\Delta\kappa$ [5], we extract bounds on these parameters for form factor scales of 1 TeV and 2 TeV (Fig. 1 b.). All other coupling parameters are set to their SM value. If only one parameter λ or $\Delta\kappa$ is non-standard, we measure at 95% CL:

$$-0.7 < \lambda < 0.7 \qquad -0.9 < \Delta\kappa < 1.0 \qquad (\Lambda_{FF} = 2 \text{ TeV})$$

5 Production of $WW, WZ \to leptons + jets$

Because of the favorable branching fractions, the WW, WZ production rates in the channel where one boson undergoes a leptonic and the other a hadronic decay, are higher than for pure leptonic decays.

Unfortunately, an extremely large QCD background from W/Z + jet production overlaps with the signal (Fig. 2 a.). However, if anomalous couplings were present, the WW, WZ production cross section would be enhanced for large boson transverse momenta, P_T^W, where—according to a Monte Carlo

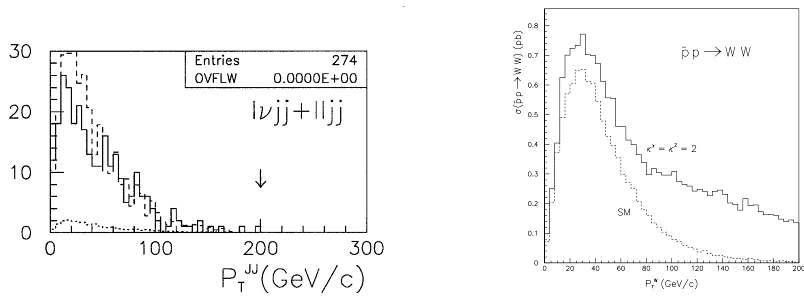


Figure 2: a.) The dijet P_T distribution of the SM signal $WW, WZ \to \ell\nu jj, \ell\ell jj$ (dots), of the background Z/W + jj (solid line) and the sum of signal plus background (dashes). b.) The WW cross section as a function of the W boson P_T for SM and non-SM couplings (dots).

study [6]—QCD background is suppressed (Fig. 2 b.). Therefore, a high P_T^W threshold of 200 GeV was chosen so that limits on anomalous couplings can be extracted without using any background subtraction.

Before specifically selecting dijets, 294 events in the $\ell\nu jj$ channel and 47 events in the $\ell\ell jj$ channel are found, where each jet with a cone size of $\Delta R_{jet} = 0.4$ has a corrected $E_T^{jet} > 30$ GeV. Requiring the dijet mass to be in the range $60 < M_{JJ} < 110$ GeV/c^2, *no* event with $P_T^{JJ} > 200$ GeV survives. The dijet reconstruction is fully efficient up to $P_T^{JJ} \sim 250$ GeV, decreasing rapidly at higher P_T^{JJ}.

Limits on the coupling parameters are calculated from the probability [5] that zero events are observed when several events with $P_T^{JJ} > 200$ GeV are predicted by a Monte Carlo simulation [6] for various anomalous couplings. Main systematic uncertainties on the yield are due to higher order QCD effects (14.3%), and jet E_T scale and resolution effects (15.8%). The bounds on

Table 3: $WW, WZ \to leptons + jets$: Coupling parameters [7] at 95% CL for form factor scales of 1 TeV and 2 TeV. For each case, the other couplings are set to their SM value.

$\Lambda_{FF} = 1$ TeV	$\Lambda_{FF} = 2$ TeV
$0.09 < g_{1,Z} < 2.05$	$0.39 < g_{1,Z} < 1.68$
$0.05 < \kappa_Z < 2.01$	$0.42 < \kappa_Z < 1.68$
$-1.67 < \lambda_\gamma < 1.60$	$-1.05 < \lambda_\gamma < 1.05$
$-0.60 < \lambda_Z < 0.58$	$-0.37 < \lambda_Z < 0.40$
$0.33 < (\kappa_\gamma = \kappa_Z) < 1.85$	$0.51 < (\kappa_\gamma = \kappa_Z) < 1.54$
$-0.51 < (\lambda_\gamma = \lambda_Z) < 0.50$	$-0.35 < (\lambda_\gamma = \lambda_Z) < 0.32$
$0.17 < \kappa_\gamma\ (HISZ) < 2.02$	$0.39 < \kappa_\gamma\ (HISZ) < 1.67$
$-0.51 < \lambda_\gamma\ (HISZ) < 0.52$	$-0.34 < \lambda_\gamma\ (HISZ) < 0.33$

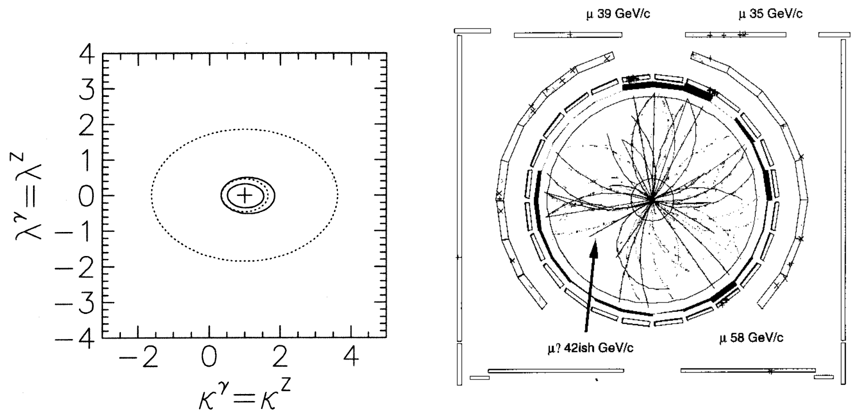


Figure 3: a.) Limit contours on the anomalous WWZ and WWγ couplings from the analysis of WW, WZ $\rightarrow \ell\nu jj$, $\ell\ell jj$ events, assuming $\lambda_Z = \lambda_\gamma$ and $\kappa_Z = \kappa_\gamma$. b.) Signature of a $ZZ \rightarrow \mu\mu\mu\mu$ candidate with M(ZZ)$\sim$ 192 GeV/c^2 in the CDF central tracking chamber.

various couplings measured in this analysis are summarized in Tab. 3. For the WWW and WWγ couplings, we measure at 95% CL:

$$-0.4 < \lambda < 0.3 \qquad 0.5 < \Delta\kappa < 0.5 \qquad (\Lambda_{FF} = 2 \text{ TeV})$$

Fig. 5 a. shows the 95% CL limit contours on λ and $\Delta\kappa$ for energy scales of 1 TeV and 2 TeV, making the assumption of matching WWZ and WWγ couplings. The results are sensitive to the choice of the P_T^{JJ} threshold within 15%.

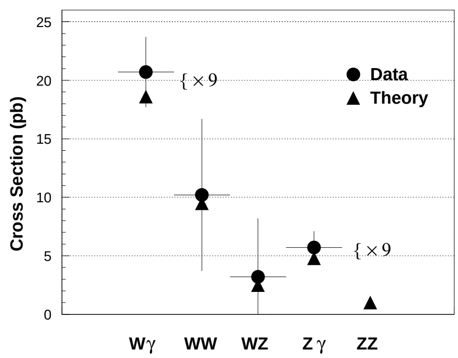
6 Summary

Fig. 4 displays a summary of the diboson cross sections measured by CDF to date. Included are preliminary results from our weak boson + photon analyses, based on a fraction of the Run I data set. They are discussed in Ref. [8].

There are three notable events collected by CDF during Run I: One ZZ candidate was found in a small data set taken during a short extension of Run I, which is not included in the analyses discussed in this paper. Four high P_T muon tracks form an invariant four-body mass of 192 GeV/c^2. This number is somewhat uncertain as one of the tracks is only incompletely reconstructed in forward direction.

Remarkable is also a $Z\gamma$ event with a photon of E_T = 192 GeV and a three body mass of $M(e^+e^-\gamma) \sim 420$ GeV/c^2 (see Ref. [9] for further details).

A rather exotic event with two electrons and two photons and a faily large $\not{E}_T$ is presented in these proceeding[10]. There is only a remote possibility that it represents a $WW\gamma\gamma$ candidate since the probability for four-boson production is extremely small ($\ll 10^{-6}$, i.e. the square of the $W\gamma$ selection rate[11]).



	WW	WZ
$\mathcal{L}$	108	113
N_{obs}	5	1
N_{bkgr}	1.2 ± 0.3	$0.3^{+0.8}_{-0.3}$
σ_{exp}	$10.2^{+6.5}_{-5.3}$	$3.2^{+5.0}_{-3.2}$
σ_{SM}	9.5	2.5

	Wγ	Zγ
$\mathcal{L}$	67	67
N_{obs}	109	31
N_{bkgr}	26.4 ± 3.6	1.4 ± 0.4
σ_{exp}	186.3 ± 33.3	51.3 ± 12.6
σ_{SM}	167.4	43.2

Figure 4: Double boson production cross sections measured by CDF compared with SM predictions. N_{obs} and N_{bkgr} are the number of observed diboson events and background, respectively. $\mathcal{L}$ is the integrated luminosity in pb^{-1}.

In view of these interesting events, we are looking forward to the next data taking in 1999 (Run II). Presently, we find good agreement of our experimental results on double boson production with SM predictions.

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